

Designing A Tanker Propellor: Structural Design

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Introduction

Marine screw propellers have not developed drastically since their first use on the steamship SS Archimedes 1839 (Royal Museums Greenwich, 2022). However, recent developments in materials and design techniques has driven a change in recent years. The arrival of reinforced polymers and the development of computational design software has drastically changed the marine propeller in a number of ways. The assignment explores the development of marine propellers with the use of finite element analysis (FEA) and optimization with a particular focus on carbon fiber reinforced plastics and their varying orientations to gain optimal performance for the variables, objectives and constraints provided. To further understand the recent developments, experimental testing has been researched and how it's linked back to the FEA process. The aims of this assignment are to gain a greater understanding of design optimization and the benefits of modern materials with varying construction techniques and to develop my skills further with computational aided engineering (CAE) packages.

1. Finite Element Analysis – History, Optimization and Development

1.1. *History and Development*

Historically design problems were solved by hand calculation and experimental data, however, with the ever growing complexity of designs causing clear limitations with hand calculation and experimental methods to grow in expense, the notion was born of more complex numerical methods i.e. finite element analysis (FEA). Circa 1950, the aerospace industry first developed early equations for FEA and these developments were further taken forward by one of the first papers published by M.J. Turner, R.W. Clough, H.C. Martin and L.J. Top in 1956. This paper laid out these methods which showed capability of 100 degrees of freedom (DOF) which was considered large at the time. By the 1960s, FEA software was developed by E. Wilson at Berkley University and from there was continued to be developed by many universities and agencies around the world (Tipton, 2017).

In the early 1980s, the digital design process was in its infancy and computer aided engineering (CAE) was still underutilized or not available in the mainstream market. A design and test approach was still taken by combining early computer aided design (CAD) and the use of experiments into an effective tool to be used in the early phases of the design process to predict, at least to some extent, the final behavior of the product to be (Eriksoon, 2000). At this stage, the only available CAD programs were 2 dimensional (Cohn, 2010) and this clearly enacted a cyclic approach to design which could reach a number of expensive iterations before reaching an acceptable solution. As computer software moved forward and hardware decreased in price, the emergence of lower cost and higher functioning CAE packages enabled the designer to incorporate simulations/virtual testing into early designs, i.e. heat transfer and stress analysis in a graphical user interface (GUI) which removed the requirement for real world building and testing (validation) and hence lowering costs. This, coupled with the time saved with the production of prototypes, provided large cost savings as shown in Figure 1.

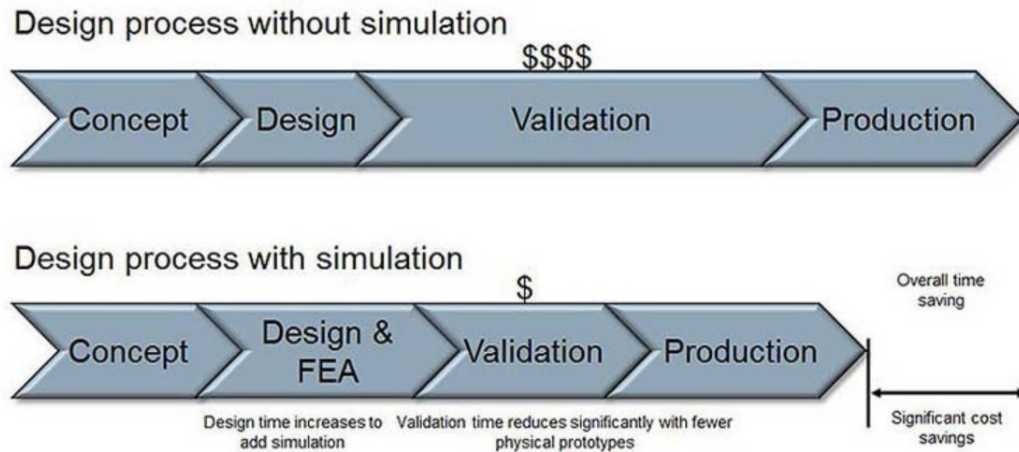


Figure 1 – Early v Modern design process (Patel, 2014)

Closer to the modern age design process came relatively recent advances in design optimization mechanics and the software has provided these options such as suggesting the design that is best suited to the conditions you specify i.e. an “optimum” design. ‘In the conventional design process, the designer would have to rely on experience or insight to come up with proposals. The analysis tool is then used to evaluate each proposal, with the designer using these analysis results or responses to choose the “best” option. The convenient feature about design optimization as a part of CAE is that you can simultaneously do both, instead of doing them one after the other as shown in Figure 2.

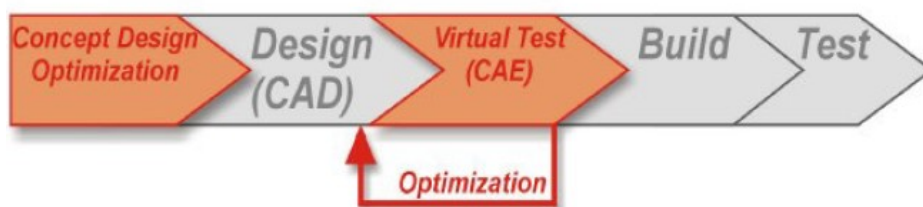


Figure 2 - Optimization design process (Altair, 2014)

The designer outlines the constraints and leaves it to the optimization tool to come up with proposals. The optimizer uses the analysis tool to decide how to change the initial design to arrive at a better one. The optimization software will suggest to you shapes and sizes that are most likely to pass the subsequent analyst’s verification. This means a tremendous change in the way we can now view CAE: Since our design has been “certified” by the optimization tool, we can approach the traditional “verification” stage with a much higher level of confidence’ (Altair, 2014). However, this can be misleading depending on the designers experience with the software and can be in some situations dangerous.

1.2. Variables, Objectives & Constraints

Before any design optimization can take place, there must three conditions present which are variables, objectives and constraints. First is the set of variables, which are the unknown quantities in the problem. The values of these will describe to the modeler the chosen design or optimal solution. The variables can then be broken down into two categories: discrete and continuous. The former indicates a variable that can take on only discrete, integer values and the latter indicates variables which can take on arbitrary real values within a given range (Nowatzki, et al., 2014). As an example, a variable could be the lay-up of a carbon fiber composite or the thickness of a material. It is worth noting that upper and lower limits are usually applied on these variables which can represent real world scenarios along with utilization of discrete variables to improve manufacturability. In the objective function, a quantity of interest is chosen to be maximized or minimized. For instance, the mass could be a chosen objective to be minimized or the design must not exceed a certain deflection value. It is common that multiple objectives are applied to a design to meet its desired outcome (Ong, 22). Lastly, design constraints are those that are generally imposed by a customer, regulations or the development organisation. Constraints may be imposed on the amount of material used or even a spacecraft that has to withstand a certain stress on its structure during take-off (Friedenthal, et al., 2015) (Yasaka & Onada, 2003). Constraints are generally hard or soft constraints where hard constraints must be met, however, soft constraints can be considered as a 'want' (Kendall, 1975). It is very important that during optimization, a design is not over constrained otherwise a feasible solution may not be found.

1.3. Optimization Techniques

There are a range of optimization techniques that can be utilized to gain the optimal solution for the design and these are discussed as follows:

- **Topology optimization (TO)** is the algorithmic process of optimizing a mechanical component or part, usually through material reduction. Topology optimization is also concerned with material distribution and how the members within a structure are connected. This is calculated according to the mechanical stresses the part will be subjected to during regular function and hence fulfilling any given constraints previously established (Carolo, 2020) (Altair, 2014). Topology optimization is typically used early in the optimization stages to identify load paths as shown in Figure 3.

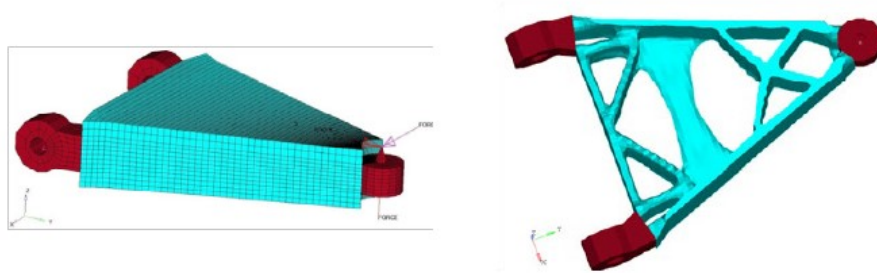


Figure 3 - Topology optimization (Altair, 2014)

- **Topography optimization** is an advanced form of shape optimization in which a design region for a given part is defined, and a pattern of shape variable based reinforcements within that region is generated. The approach in topography optimization is similar to the approach used in topology optimization, except that shape variables are used rather than density variables (Darge, et al., 2014). Topography optimization is generally utilized on thin structures to enhance their rigidity as can be seen in Figure 4.

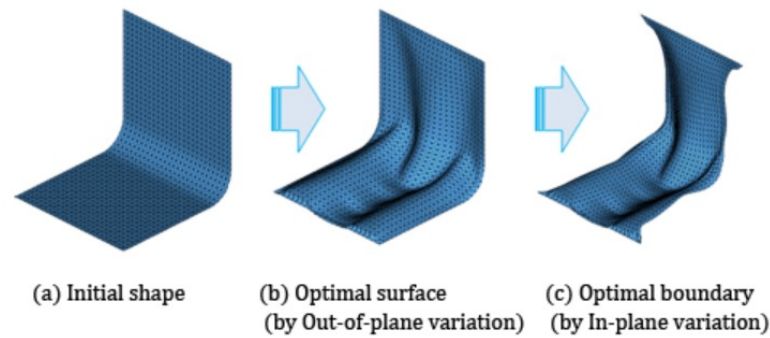


Figure 4 - Topography optimization example (Heney, 2015)

- **Topometry / size optimization** is a technique that allows finding the optimal distribution of sizing dimensions of elements in a given designable region. This capability allows performing sizing optimization on each element individually, whereas in traditional sizing it is performed by groups. Like topology, optimization this capability allows finding the optimal location of void material but it can produce continuous variation of the geometric properties. The use of this technique allows designers to find innovative designs with less effort. It also allows the designer to explore a larger design space than with traditional sizing optimization (Leiva, 2004).
- **Shape optimization** - The shape of a structure can be optimized by controlling its boundary (Larsson, 2016). Shape optimization is a tool of great use when aiming to improve the structure locally by analyzing areas with high stresses, as these areas can be shape optimized in order to lower the stress level (Mansouri & Norman, 2009). You use shape optimization at the end of the design process when the general layout of a component is fixed, and only minor changes are allowed by repositioning surface nodes in selected regions. A shape optimization starts with a finite element model that needs minor improvement or with the finite element model generated by a topology optimization (Dassault Systèmes, 2011).

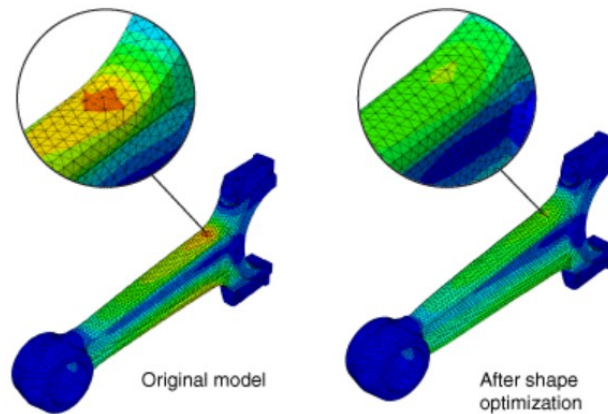


Figure 5 - Effect of shape optimization (Dassault Systèmes, 2011)

- **Composite optimization** adjusts a design to ensure the set-up of the plies is the most effective for the load action that the design is trying to achieve. Generally the process is broken down into three distinct steps:

- Phase 1 – Concept stage is where the free size optimization creates the thickness distribution for each fiber angle
- Phase 2 – Dimension stage is where the discrete size optimization calculates the optimal number of each ply shape of each fiber angle
- Phase 3 – Sequence stage is where the optimal stacking sequence is calculated

(Kriesch & Wehr, 2012)

An example of the composite design process can be seen in Figure 6 which shows the level of compliance between each stage in the process.

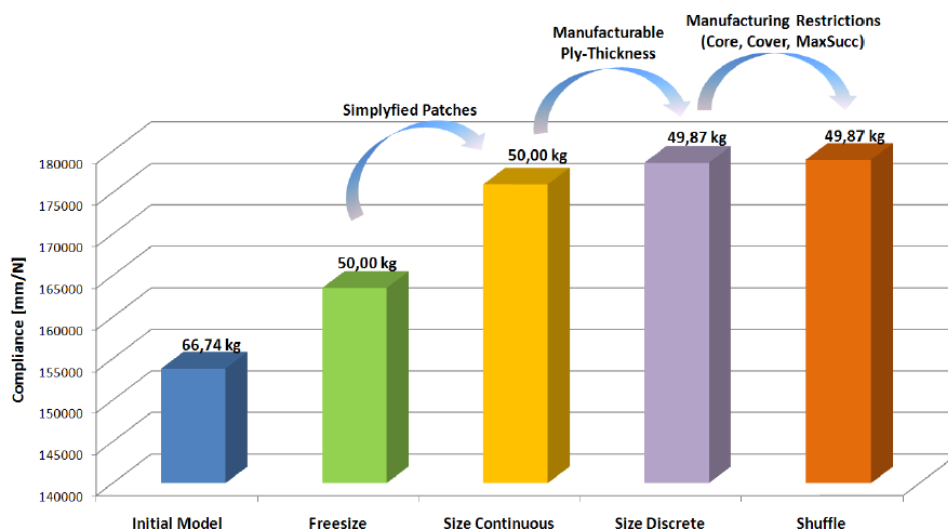


Figure 6 - Overview of composite optimization results (Kriesch & Wehr, 2012)

1.4. *Influence FEA has on the Design Process and Future Developments*

FEA optimization aids the design process in a number of ways. Initially, designs are developed digitally removing the need for expensive prototypes such as crash tests. FEA allows you to develop a digital model for the object and study the stresses it encounters in the real world. With FEA, you can model the interior and exterior of an object, thereby allowing you to point out design flaws that are vulnerable to external conditions. As such, users can correct these design problems through finite element analysis that enables the visualization of stresses, strains, and thermal variations. In addition to these points, FEA software-based simulation models are far more accurate than physical models that are developed manually. This is why FEA has been the preferred option for most engineers, designers, and others for a number of years (Kanade, 2022). Ultimately, FEA speeds the process of design, lowers costs and simplifies the whole process.

FEA has come a long way since its beginnings to coincide with ever increasing complexity of designs to be analyzed. The accuracy of the software is improving and the hardware capabilities are increasing year on year. The future of FEA and optimization could be a live stream of data feeding into the software to predict reactions/outcomes before they happen. For instance, nuclear reactors have been modelled with FEA for a number of years (Zienkiewicz, et al., 1972). However, in the absence of evidence where by providing live feedback to predict future reactions, engineers at present make assumptions and best informed guesses alongside snapshot point in time data. This streaming information would create an ever changing model that reacts to certain scenarios of data input which would remove a number of the approximations made. Clearly, this immense amount of data feeding into a live model and the sheer computing power required to make this happen would be very large, but the possibilities would be endless with many applications that could be considered throughout all industries.

2. Propellor Finite Element Analysis Model

2.1. Steel Propellor Blade Loading Adjustment

The original steel propellor blade that was designed had a 5kN uniformly distributed load case which is not true to real world propellor loadings as seen in Figure 7. Taking into account that pressure is a force per unit area, it can be said that the pressure distribution over the blade can be directly linked to the force over that area. Utilizing this approximate pressure distribution and the data from assignment one, the total load was calculated utilizing a lift force equation as follows:

$$Lf = 0.5(Cl \times \rho \times v^2 \times A)$$

Where:

Lf	= Lift force
Cl	= Coefficient of lift
ρ	= Density of water
A	= Area

Based on Table 1 utilizing an angle of attack of 10 degrees we will assume the coefficient of lift is 0.3. The Area is 8.4m² and the density of sea water is 1029kg/m³.

Angle of attack (α)	Lift coefficient				
	C_y (CFD_Xiao)	C_y (CFD_Lars)	C_y (Exp.)	C_y (CFD_Xiao) and C_y (CFD_Lars) error (%)	C_y (CFD_Xiao) and C_y (Exp.) error (%)
10	0.326	0.346	0.374	-5.7	-12.8
20	0.598	0.573	0.623	4.4	-4.0
30	0.751	0.794	0.756	-5.4	-0.7
35	0.705	0.770	0.739	-8.4	-4.6

CFD: computational fluid dynamics.

Table 1 - Lift coefficients for varying angles of attack (Yang, et al., 2019)

So:

$$Lf = 0.5(0.3 \times 1029 \times 3.57^2 \times 8.4)$$

$$Lf = 16.52 \text{ kN}$$

The calculated force is the total force acting over the whole portion of the propellor blade can be seen as Lf. It can now be approximately distributed as per the pressure distribution as shown in Figure 7.

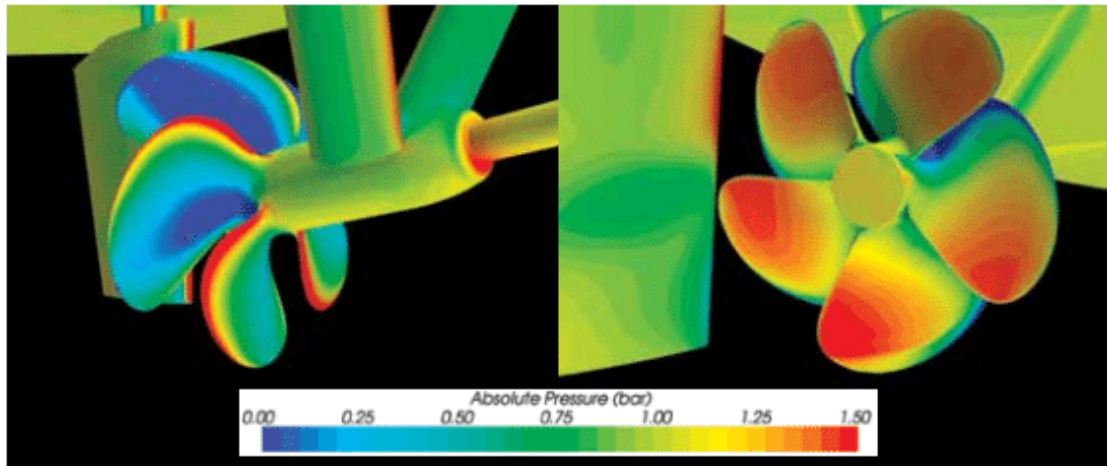


Figure 7 – General pressure distribution over a propellor blade (Stockdill, 2012)

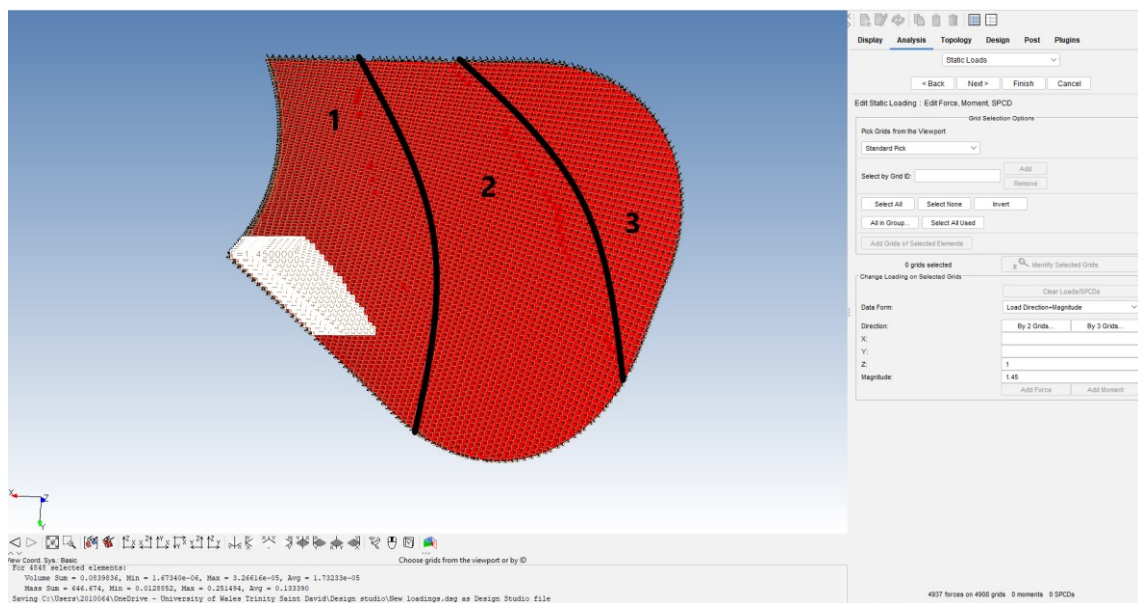


Figure 8 – Amended load case to approximately represent real world scenarios where three is the high pressure area.

Based on the research for the loadings and the pressure distribution, the blade was loaded as shown in Table 2.

Area	Number of grids	Load per grid (N)	Total
1	2066	1.45	9kN
2	1870	2.4	4.4kN
3	1000	9	3kN
			16.4kN

Table 2 - Distribution of loading on blade

N.B. With freehand separation of the areas it is difficult to accurately distribute the load to 16.52kN as per the calculation.

2.2. Composite Layup of the Propellor Blade

As can be seen in Figure 9 the composite material was laid up at 45 degree angles made of 5 plies.

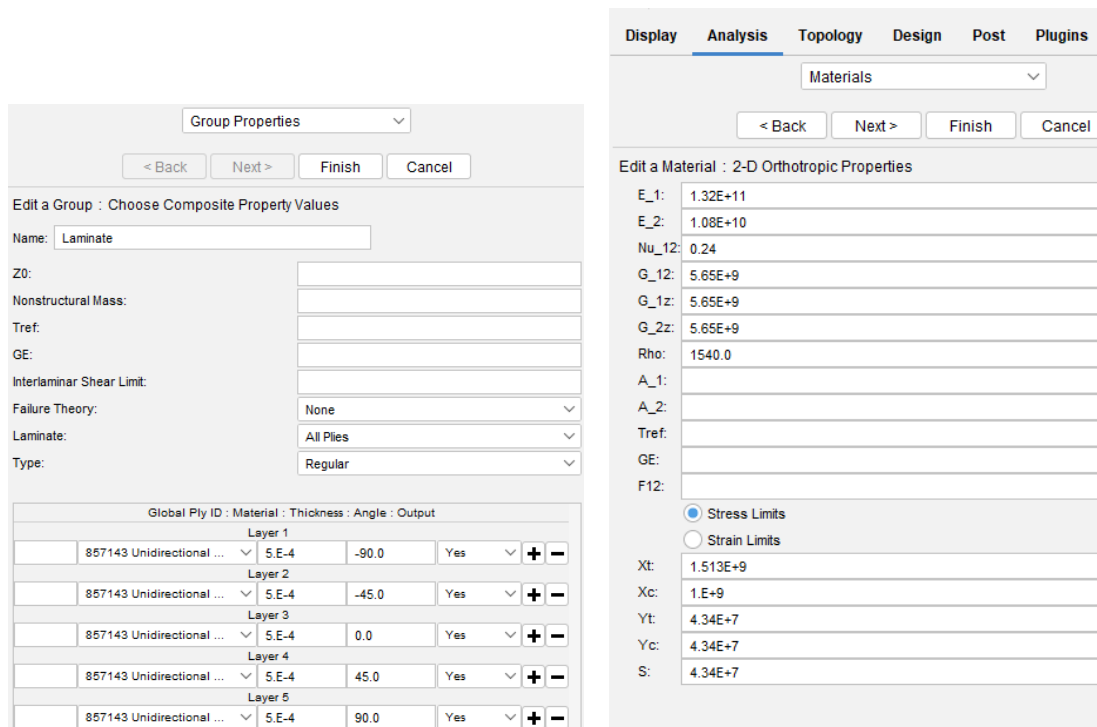


Figure 9 - Composite properties and lay up

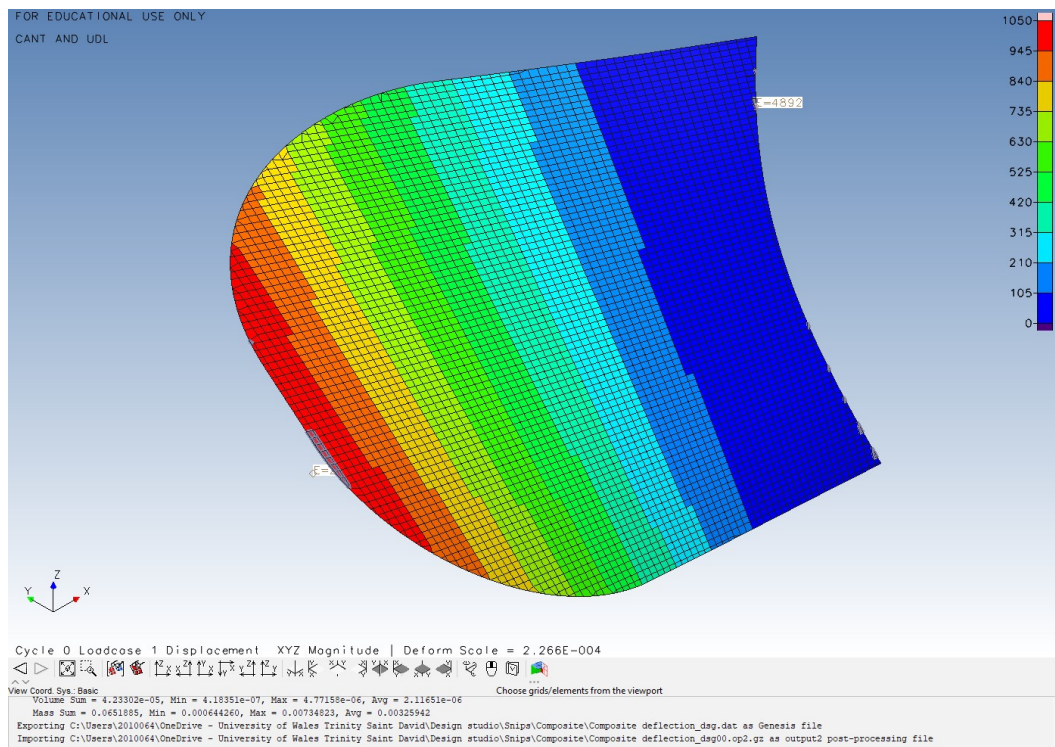


Figure 10 - Composite layup with a deflection of 1050m

The 1050mm deflection shown in Figure 10 by the composite layup clearly indicates that the propellor blade would have failed during the loading scenario. The reason why Design Studio does not recognize this is the program is running as a linear solver and does not take into account for any plastic deformation i.e. material property changes. By changing to the composite material, the weight has dropped significantly to 65kg from the original 646kg for the steel blade, however, the deflection is clearly over the objective of a 100mm limit.

3. Optimization of the Composite Propellor Blade

The composite blade has now been optimized to meet the objective of no more than a 100mm deflection at its extent while minimizing its mass.

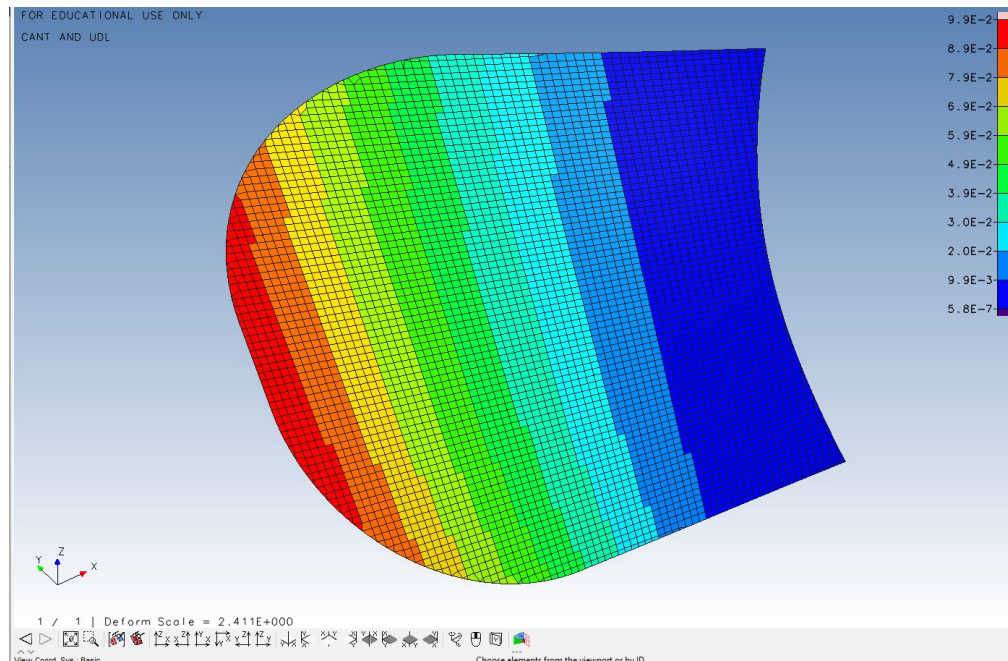


Figure 11 - Optimized propellor deflecting to 99mm at its extremity.

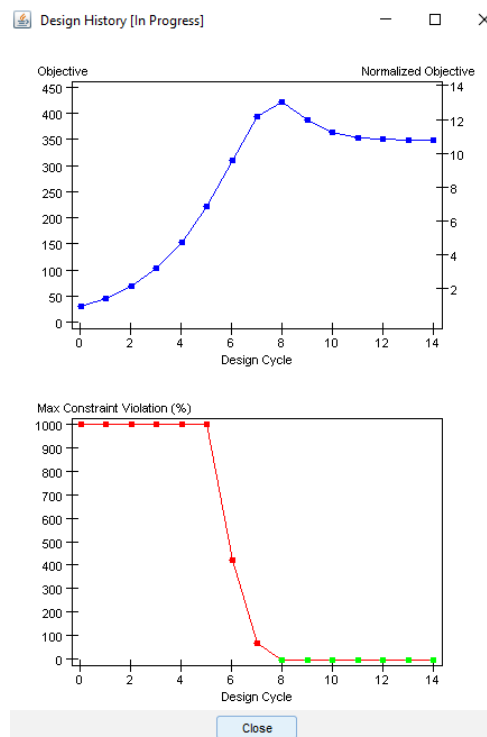


Figure 12 – 14 optimization cycles taken to achieve compliance

Figures 11 and 12 show the propellor achieved compliance within 14 optimization cycles. At design cycle 5, the model was violating its constraints by a 1000%, which shows that the mass was being concentrated on via calculation. However, the software was not meeting its deflection values. During these stages, the software ran through a number of iterations and eventually converged on a solution that is an optimal condition for the constraints and objectives set.

DESIGN CYCLE HISTORY		
DESIGN CYCLE	OBJECTIVE FUNCTION	MAXIMUM CONSTRAINT VIOLATION
0	3.2334E+01	999.9%
1	4.7807E+01	999.9%
2	7.1120E+01	999.9%
3	1.0573E+02	999.9%
4	1.5516E+02	999.9%
5	2.2379E+02	999.9%
6	3.1061E+02	425.7%
7	3.9499E+02	69.0%
8	4.2204E+02	0.0%
9	3.8938E+02	0.0%
10	3.6506E+02	0.0%
11	3.5508E+02	0.0%
12	3.5185E+02	0.0%
13	3.4978E+02	0.0%
14	3.4910E+02	0.0%
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DESIGN VARIABLE HISTORY					
DESIGN CYCLE	DESIGN VARIABLE	DESIGN VARIABLE	DESIGN VARIABLE	DESIGN VARIABLE	DESIGN VARIABLE
	1	2	3	4	5
	L1THK	L2THK	L3THK	L4THK	L5THK
0	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04
1	6.7519E-04	7.5249E-04	8.3807E-04	7.4284E-04	6.8779E-04
2	9.3246E-04	1.1281E-03	1.3715E-03	1.1019E-03	9.6489E-04
3	1.3064E-03	1.6792E-03	2.1946E-03	1.6259E-03	1.3690E-03
4	1.6005E-03	2.4474E-03	3.9135E-03	2.3087E-03	1.7265E-03
5	1.8158E-03	3.3572E-03	7.0525E-03	3.0599E-03	2.0176E-03
6	1.7975E-03	4.1296E-03	1.2413E-02	3.5910E-03	2.0846E-03
7	1.4660E-03	4.1432E-03	1.9860E-02	3.3869E-03	1.6839E-03
8	8.9005E-04	3.0605E-03	2.5458E-02	2.3064E-03	9.1678E-04
9	3.3886E-04	1.6657E-03	2.6583E-02	1.1609E-03	3.5726E-04
10	1.1320E-04	8.7839E-04	2.6597E-02	5.2646E-04	1.1030E-04
11	1.0000E-04*	4.8450E-04	2.6493E-02	2.7697E-04	1.0000E-04*
12	1.0126E-04	2.7095E-04	2.6575E-02	1.5667E-04	1.0118E-04
13	1.0000E-04*	1.5248E-04	2.6586E-02	1.0581E-04	1.0000E-04*
14	1.0000E-04*	1.0000E-04*	2.6592E-02	1.0000E-04*	1.0000E-04*

* = DESIGN VARIABLE AT UPPER OR LOWER BOUND

Figure 13 - Design cycle history showing the changes in layer thickness throughout the optimization cycle

During the design cycle, the software converged on a solution that made the middle layer the thickest which will give the composite layup the highest stiffness. At this stage, for the propellor to reach its objective, the mass of the composite was increased to 349kg which is approximately an increase of 5 times the original mass.

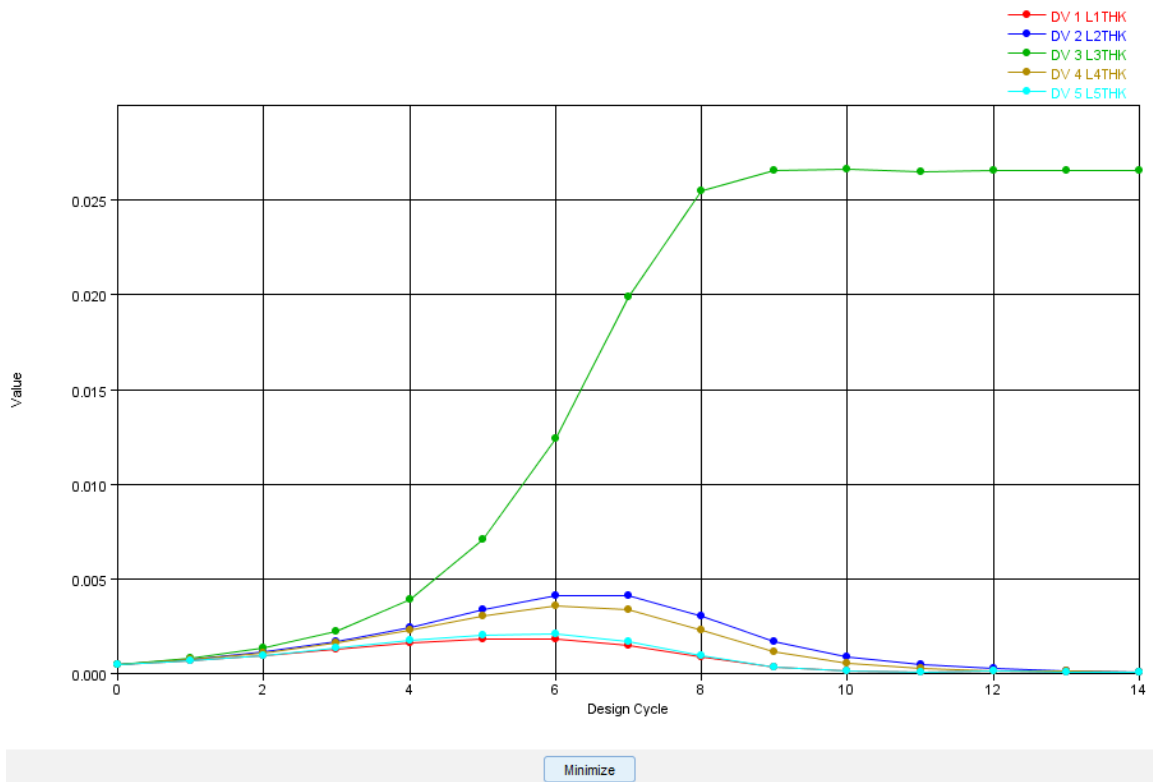


Figure 14 - Graphical representation of layer thickness over design cycles

As can be seen in Figure 14 by design cycle 7, the software's main objective was to minimize weight as the deflection objective had been met.

3.1. Utilization of Discreet Variables to Aid Manufacturability

Based on the results from the initial optimization, it can be seen that L3THK was 2.6592×10^{-2} which would not be a feasible thickness to manufacture. Taking this into account, discreet variables were set to ensure the solution met real world values which would improve its manufacturability.

DESIGN VARIABLE HISTORY					
DESIGN CYCLE	DESIGN VARIABLE 1 L1THK	DESIGN VARIABLE 2 L2THK	DESIGN VARIABLE 3 L3THK	DESIGN VARIABLE 4 L4THK	DESIGN VARIABLE 5 L5THK
0	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04
1	6.7519E-04	7.5249E-04	8.3807E-04	7.4284E-04	6.8779E-04
2	9.3246E-04	1.1281E-03	1.3715E-03	1.1019E-03	9.6489E-04
3	1.3064E-03	1.6792E-03	2.1946E-03	1.6259E-03	1.3690E-03
4	1.6005E-03	2.4474E-03	3.9135E-03	2.3087E-03	1.7265E-03
5	1.8135E-03	3.3585E-03	7.0507E-03	3.0611E-03	2.0191E-03
6	1.8019E-03	4.1213E-03	1.2431E-02	3.5843E-03	2.0774E-03
7	1.4679E-03	4.1300E-03	1.9882E-02	3.3755E-03	1.6747E-03
8	8.4483E-04	2.9681E-03	2.5618E-02	2.2499E-03	9.2245E-04
9	3.2732E-04	1.6625E-03	2.6451E-02	1.1543E-03	3.8872E-04
10	1.3755E-04	8.8548E-04	2.6520E-02	5.6354E-04	1.2694E-04
11	1.0000E-04	4.5740E-04	2.6495E-02	3.2189E-04	1.0000E-04
12	1.0094E-04	2.7664E-04	2.6579E-02	1.5516E-04	1.0089E-04
13	1.0000E-04*	1.5588E-04	2.6586E-02	1.0456E-04	1.0000E-04*
14	1.0000E-04*	1.0000E-04*	2.6594E-02	1.0000E-04*	1.0000E-04*
15	1.0000E-04*	1.0000E-04*	2.6594E-02	1.0000E-04*	1.0000E-04*
16	2.0000E-04	2.0000E-04	2.6600E-02	2.0000E-04	2.0000E-04

Figure 15 - Discreet optimization results

The thickness of L3THK has now been optimized taking into account the discreet variables that the software was allowed and has now made the largest layer to a manufacturable tolerance. This has come at a cost though as the weight has increased to 354kg which is an increase of 5kg.

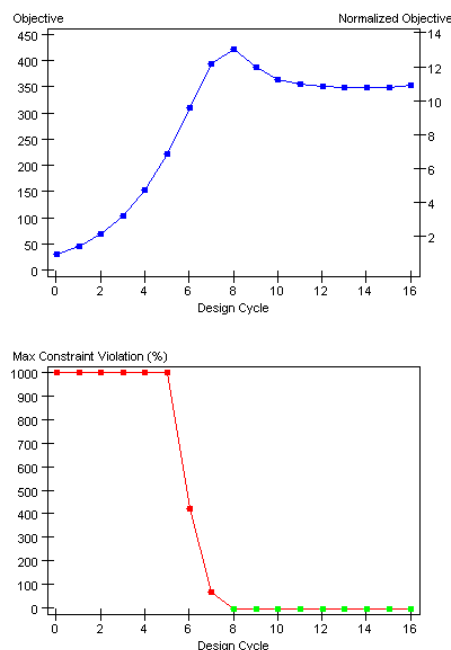


Figure 16 - Design cycles of discreet optimization stage

3.2. Overall Results For Comparison

The results in Table 3 show that the stiffness to weight ratio has increased in the latter optimization runs. The mass/weight has halved, while holding a much lower deflection for the comparable load. There are two spurious figures which are highlighted in red due to the software not showing the conscious ability to identify where the blade would have broken, hence why the figures show a very low stiffness.

Run	Thickness (m)	Deflection (m)	Mass (Kg)	Weight (Kg)	Load (kN)	Stiffness(kN/m)	Stiffness/Weight (N ² /m)
Steel baseline	0.01	1.1	647	6347.07	16.483	14.98	1.73E-04
Composite	0.0025	105	32	313.92	16.483	0.156	3.34E-01
Optimised composite	0.027	0.099	349	3423.69	16.483	166.5	2.89E-05
Discreet composite	0.0274	0.097	354	3472.74	16.483	169.93	2.79E-05

Table 3 - Stiffness to weight ratio for each material/optimization

Table 1 indicates the layup of the composites as the design evolved. It's interesting to note that the number of plies increased in the outer layers when the discreet variables were introduced. This clearly added some weight at the expense of manufacturability, however, the deflection was reduced by 2mm.

	L1	L2	L3	L4	L5	Total
Comp	0.0005	0.0005	0.0005	0.0005	0.0005	0.0025
Plys	5	5	5	5	5	25
OPT comp	0.0001	0.0001	0.02659	0.0001	0.0001	0.02699
Plys	1	1	265.9	1	1	269.9
DISC comp	2.00E-04	2.00E-04	2.66E-02	2.00E-04	2.00E-04	0.0274
Plys	2	2	266	2	2	274

Table 4 – Composite, optimized and discreet variable layup of the composite structure at each stage

4. Testing of Marine Propellers

In order to correlate the FEA results for the propellor, it would be prudent to test the propellor as close to a real world scenario as possible. As previously discussed in the initial module assignment, this leaves two primary options of tow tank testing and cavitation tunnel testing. For the purpose of deflection, the cavitation tunnel would produce the most obtainable results given that the propellor blade has no advance movements within the tunnel as oppose to the towing tank (Tupper, 2013). The propellor blade should be fixed onto a hub as per its full original assembly and mounted in an uninterrupted flow path as seen in Figure 17 with the drive shaft downstream (Bertram, 2012).

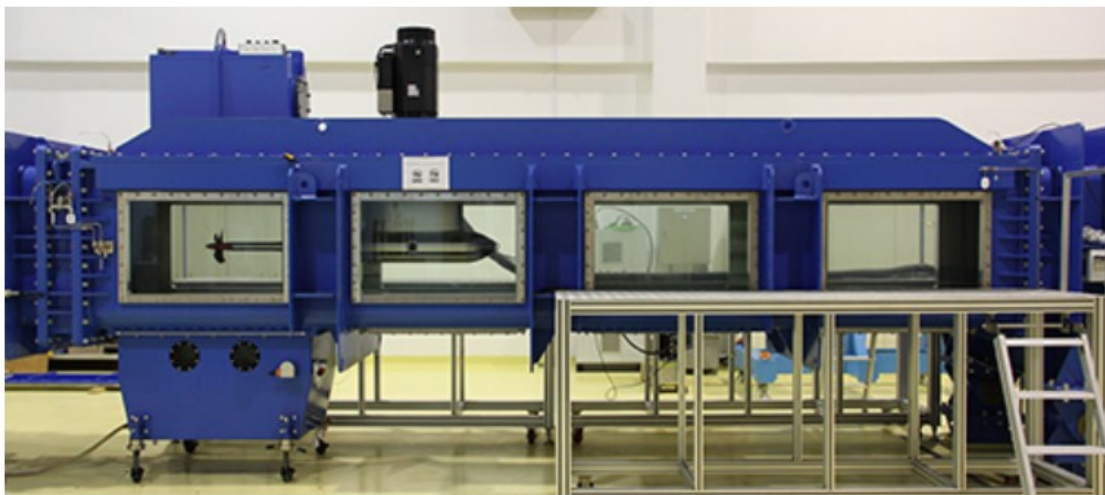


Figure 17 - Cavitation tunnel with mounted propellor (State Key Laboratory Of Ocean Engineering, n.d.)

This will ensure the propellor blade is receiving a laminar flow of water which will reflect the FEA models loading case which was decreasing over certain regions of the blade. This pressure can be measured with pressure sensors/tappings that are distributed over the model, which will indicate the load on the blade (Molland & Turnock, 2022). To introduce the load on the propellor, the RPM and flow of water can be set to replicate the FEA model forces. These should be correlated to the FEA model before any data acquisition begins and it is imperative that all calibration has been carried out on all test equipment. Data acquisition will primarily be gathered utilizing stroboscopic lights which will give the effect that the propellor is stationary and a high speed camera is used to record the data (Bertram, 2012). Reference marks will be put on the unloaded propellor and the reference data will be compared with the loaded blade which will indicate deflection. The experimental data can then be directly correlated to the FEA model for any discrepancies to be investigated.

5. Standards Related to Marine Propellers

For the calculation of propellers, the primary standard that set out the basic principles and calculations required for propeller design are the 'DNV-CG-0039' guidelines. The guidelines direct the designer on how to calculate high and low cycle stresses along with the loading, skew and bending moment coefficients. The document also addresses the designs with regards to CFD, FEA and fatigue strength of the specific blade classes. In addition, 'DNV-RU-SHIP Pt.4 Ch.5. Rotating machinery - driven units' covers the criteria for blade dimensions and classification along with the arrangement and vibration characteristics of propellers (DNV, 22).

In the instance that a propeller is designed with the use of CFRP as in the case of this assignment, then the 'Bureau Veritas guidance document 'NI 663 DT R00 E' should be adhered to. This guidance document defines the procedures and requirements for certification, design, construction, installation, test, trials and surveys of propellers, made of composite material, to be fitted on board ships classed with the Society. The document covers all aspects from the material certification and selection through to testing and sea trials for certification (Bureau Veritas, 2020).

There are specific standards to which propeller design is governed to whereby the propeller must not exceed a maximum noise under normal operating conditions. This standard is among other nations standards; 'BSI BS ISO 20233-1 - Ships and marine technology — Model test method for propeller cavitation noise evaluation'. This standard particularly explores the removal of propeller noise at design stage and discusses explicit tests to run to gain an understanding of the level of noise and the location.

With regards to testing of propellers, the International Towing Tank Conference (ITTC) has a number of documents that address the uncertainty of testing and the procedures that should be followed for each test scenario (tanks, cavitation tunnels and load tests). These documents are all listed within the ITTC – Recommended Procedures and Guidelines register and cover all aspects from but not limited to ice breaking, wave generation, cavitation testing and calibration of key instruments (International Towing Tank Conference, 2021).

6. Conclusion

It's clear that design processes have improved over recent years and optimization has greatly reduced time, cost and effort by streamlining the design process. There are some pitfalls with the utilization of CAE with the largest being the skill of the engineer running the software. Dangerous or non sensical designs could be produced if the engineer does not have the experience or knowledge to identify non-conformities in designs. In the other vein, designs could be produced that are not optimized to their full potential which then increases manufacturing costs due to material usage and processing times. Ultimately, with all designs there will be a tradeoff between the optimal design and a sensible design which fits the real world criteria. For the utilization of CAE and open water testing for the design of propellers, the discrepancies in results are very close in terms of accuracy. In my subjective opinion, shipping companies and designers will begin to rely heavier on the CAE environment for validation rather than testing facilities primarily due to cost implications.

Bibliography

Kriesch, M. & Wehr, A., 2012. *Composite Optimization with OptiStruct11 on the Example of a Formula Student Monocoque*. s.l.:Altair.

Altair, 2014. *Practical Aspects of Structural Optimisation*. Michigan: Altair Engineering Inc.

Bertram, V., 2012. *Practical Ship Hydrodynamics*. 2nd ed. Amsterdam: Elsevier Ltd.
British Standards Institution, 2015. *BS ISO 484-1:2015*. s.l.:BSI.

Bureau Veritas, 2020. *Propeller in Composite Materials*, Neuilly-sur-Seine: Bureau Veritas.

Carolo, L., 2020. *What Is Topology Optimization?*. [Online]
Available at: <https://all3dp.com/2/topology-optimization-simply-explained/>

Cohn, D., 2010. *Digital Engineering 24/7*. [Online]
Available at: <https://www.digitalengineering247.com/article/evolution-of-computer-aided-design>

Darge, S., Shilwant, S. C. & Patil, S. R., 2014. Finite element analysis and topography optimization of lower arm of double wishbone suspension using abacus and optistruct.. *Int. Journal of Engineering Research and Applications*, 4(7), pp. 112-117.

Dassault Systèmes, 2011. *Abaqus Analysis User's Manual*. Maastricht: Dassault Systèmes.

DNV, 22. *DNV-RU-SHIP Pt.4 Ch.5*, Bærum: DNV.

Eriksoon, M., 2000. *Efficient Use of Finite Element Analysis in Early Design Phases*. Maryland, USA, American Society of Mechanical Engineers, pp. 1009-1016.

Friedenthal, S., Moore, A. & Steiner, R., 2015. Residential Security System Example Using the Object-Oriented Systems Engineering Method. *A Practical Guide to SysML (Third Edition)*, pp. 417-504.

Gokhale, N. S., Bedekar, S. V., Thite, N. A. & Deshpande, S. S., 2008. *Practical Finite Element Analysis*. Maharashtra, India: Finite To Infinite.

Heney, P., 2015. *Design optimization: Topology and much more*. [Online]
Available at: <https://www.3dcadworld.com/design-optimization-topology-and-much-more/>

International Towing Tank Conference, 2021. *ITTC – Recommended Procedures and Guidelines*, s.l.: ITTC.

Jiu, L. et al., 2020. A CAD-oriented structural topology optimization method. *Computers and Structures*.

Kanade, V., 2022. What Is Finite Element Analysis? Working, Software, and Applications. *SpiceWorks*, 13 October.

Kendall, J. W., 1975. Hard and soft constraints in linear programming. *The International Journal of Management Science*, 3(6), pp. 709-715.

Larsson, R., 2016. *Methodology for Topology and Shape Optimization: Application to a Rear Lower Control Arm*, Goteburg: Chalmers University of Technology.

Leiva, J. P., 2004. *Topometry Optimization: A New Capability to Perform Element by Element Sizing Optimization of Structures*. Albany, Vrand.

Leiva, J. P., Watson, B. C. & Kosaka, I., 2007. *A Comparative Study of Topology & Topometry Structural Optimisation Methods Within The Genesis Software*. Frankenthal, Dynamore GMBH, pp. 23-32

Mansouri, A. & Norman, D., 2009. *Strategy Development of Structural Optimization in Design Processes*, Linköping: Linköping University.

Molland, A. F. & Turnock, S. R., 2022. *Marine Rudders, Hydrofoils and Control Surfaces*. 2nd ed. Amsterdam: Elsevier.

NASA, n.d. *The Lift Equation*. [Online]
Available at: <https://www.grc.nasa.gov/www/k-12/rocket/lifteq.html#:~:text=The%20lift%20equation%20states%20that,times%20the%20wing%20area%20A.&text=For%20given%20air%20conditions%2C%20shape,Ci%20to%20determine%20the%20lift.>
[Accessed 25 October 2022].

Nowatzki, T. et al., 2014. *Optimization and Mathematical Modeling in Computer Architecture*. New York: Springer.

Ong, D. C., 22. *Statistics and Analytics for the Social and Computing Sciences*, s.l.: Bookdown.

Patel, M., 2014. *HightechCAE.com*. [Online]
Available at: <https://www.hitechcae.com/wp-content/uploads/2014/08/fea.jpg>
[Accessed 18 October 2022].

Sid, C., Baldomir, A. & Hernandez, S., 2020. Probability-damage approach for fail-safe design optimization (PDFSO). *Structural and Multidisciplinary Optimization*, Volume 62. State Key Laboratory Of Ocean Engineering, n.d. *Cavitation Tunnel*. [Online]
Available at: <https://oe.sjtu.edu.cn/EN/list.php?id=46&t=3>

Stockdill, B., 2012. *Propeller Cavitation Analysis with Computational Fluid Dynamics*. [Online]
Available at: <https://gcaptain.com/propeller-cavitation-analysis/>

Tipton, R., 2017. A Brief History of Finite Element Analysis. *Northern Lights Solutions*, 4 January.

Tupper, E. C., 2013. *Introduction to Naval Architecture*. 5th ed. Oxford: Butterworth-Heinemann.

Vanderplaats, G. N., 2007. *Multidiscipline Design Optimization*. Monterey: Vanderplaats Research & Development.

Wakes, S., Fahey, M. & Shaw, C. T., 2010. Enhancing and Optimising the Use of Engineering Tools within the Design Process. *Design Principles & Practice: An International Journal*, 4(1), pp. 23-33.

Yang, X., Yin, Y. & Liang, J.-J., 2019. Numerical study on the hydrodynamic performance of the semi-spade rudder and propeller. *Advances in Mechanical Engineering*, 11(1), pp. 1-18.

Yasaka, T. & Onada, J., 2003. Spacecraft Structures. *Encyclopedia of Physical Science and Technology (Third Edition)*, pp. 449-461.

Zienkiewicz, O. C., Owen, D. R. J., Phillips, D. V. & Nayak, G. C., 1972. Finite element methods in the analysis of reactor vessels. *Nuclear Engineering and Design*, 20(2), pp. 501-507.